at all upon either steam or carbon dioxide. Magnetic oxide of iron is the final product of the action of steam or of carbon dioxide at a high temperature upon metallic iron:—

$$3Fe + 4H_2O = Fe_3O_4 + 4H_2.$$
$$3Fe + 4CO_2 = Fe_3O_4 + 4CO.$$

Now, metallic iron has been detected in basalts and some other rocks by Andrews ('Brit. Assoc. Rep.,' 1852, Sections, p. 34), and by other observers (*e.g.*, G. W. Hawes, 'Amer. J. Sci.,' Ser. 3, vol. 13, p. 33), and I have verified this observation in the case of the gabbro of Loch Coruisk. But it must be remembered that both the reactions indicated in the equations just given are reversible, and therefore the presence of metallic iron along with the magnetic oxide in such rocks cannot be taken by itself as final proof that the oxide and the associated gases, hydrogen and carbonic oxide, are the products of the action of steam and carbon dioxide upon metallic iron. The presence of marsh gas in these rocks and the production of large quantities of hydrocarbonous gases, as well as liquid petroleum, in many parts of the earth's surface, tend to support the view, which is apparently gaining ground, that in the interior of the earth's crust there are large masses, not only of metal but of compounds of metals, such as iron and manganese, with carbon. Assuming the existence of such material, it is easy to conceive how, by the action of water at an elevated temperature, it may give rise to metallic oxides and mixtures of hydrogen with paraffinoid and other hydrocarbons. This view was put forward some years ago by Mendelejeff ("Principles of Chemistry," Translation by Kamensky and Greenaway, vol. 1, 364—365), and it has lately received further support from the results of the study of metallic carbides, which we owe especially to Moissan ('Roy. Soc. Proc.,' vol. 60, 1896, pp. 156—160).

"On Lunar Periodicities in Earthquake Frequency." By C. G. KNOTT, D.Sc., Lecturer on Applied Mathematics, Edinburgh University (formerly Professor of Physics, Imperial University, Japan). Communicated by JOHN MILNE, F.R.S. Received November 4, 1896,—Read February 4, 1897.

(Abstract.)

1. *Introduction.*—The paper is a discussion of Professor Milne's Catalogues of 8331 earthquakes, recorded as having occurred in Japan, during the eight years 1885 to 1892 inclusive. These catalogues, forming vol. 4 of the 'Seismological Journal of Japan,'

are unquestionably the most complete ever constructed for an earthquake-disturbed country.

The discussion is really a working out of certain lines suggested in a paper on "Earthquake Frequency," communicated by me in May, 1885, to the Seismological Society of Japan, and published in vol. 9 of the 'Transactions' of that Society. In that paper I pointed out the importance of subjecting earthquake statistics to some strict form of mathematical analysis, and gave a simple arithmetical process for separating the annual and semi-annual periods in earthquake frequency. The results then obtained have been fully corroborated by Dr. C. Davison in his paper "On the Annual and Semi-annual Seismic Periods" ('Phil. Trans.,' vol. 184, 1893); and my suggestion that the annual period is connected with barometric pressure is also strongly supported by Dr. Ferd. Seidl in his pamphlet 'Die Beziehungen zwischen Erdbeben und Atmosphärischen Bewegungen' (Laibach, 1895). The semi-annual period, which was first clearly brought into evidence in my earlier paper, does not admit of a very ready explanation.

In my paper of 1885 I also considered in some detail the various tidal actions which might reasonably be supposed to have a determining influence on earthquake frequency. From lack of material it was not possible at that time to make a satisfactory search for lunar periodicities; but the remarkable fulness of information contained in Professor Milne's latest catalogues tempted me to undertake the labour involved in (first) tabulating the statistics in terms of lunar periods, and (second) analysing harmonically the tables so prepared.

2. *The Lunar Daily and Half-daily Periods.*—In one of the catalogues the earthquakes are classed according to district. Districts 1 to 6 lie on the N.E. and E. coasts of Japan, reckoning from the north; districts 6 to 11 on the S. coast; and 12 to 15 on the W. coast. Districts 6 and 7 are the most important, the former being the region including Tokyo and Yokohama, and the latter the region including Nagoya, which was the scene of the destructive earthquake of October 28, 1891. The investigation into a possible lunar daily period is conveniently based upon this classification into districts. Had that not been done by Professor Milne the labour involved in taking into account differences in local time would have been enormous; for, to compare the time of occurrence of a recorded earthquake with the immediately preceding meridian passage of the moon, it was necessary to apply corrections for longitude and local time.

The statistics for each district were, in the first instance, separated out and tabulated according to time of occurrence, estimated in hours after the immediately preceding passage of the moon. The method

is explained in full in the paper. To lighten in some measure the labour of the harmonic analysis, certain districts were thrown together to form a district group. Table I contains the number of earthquakes in each district or district group, which formed the material for discussion.

Table I.

District.	Number of earthquakes.	Description of district.
1	397	Nemura.
2—5	627	E. coast.
6	1432	S.E. corner.
7	3632	Nagoya, &c.
8	245	Kii Channel.
9—10	335	E. and S. of Kyushu.
11	384	W. of Kyushu.
12	112	W. coast of Main Island.
13	118	
14—15	145	

Of the tabulated numbers for each district or district group, overlapping means of every successive five were taken, and these were divided by the mean of all. The numbers so obtained represent relative frequencies throughout the lunar day, and are given in Table II, which also contains a like series for all the earthquakes taken in combination.

The most important are the frequencies for districts 6 and 7, and also for all combined. They are shown graphically in the figure (p. 461).

Each series of numbers was then discussed by harmonic analysis in accordance with the Fourier expansion

$$x = 1000 + \sum_{n=1}^{n=\infty} c_n \sin n\left(\frac{360t}{25} + \alpha_n\right),$$

where x is 1000 times the relative frequency at time t, estimated in hours after the meridian passage of the moon, and where the amplitude c_n and the phase α_n are to be calculated. The amplitudes and phases for the first four harmonics are given in Table IV.

There is a tendency for the second harmonic amplitude to be greater than the first, while in half the number it is the greatest of all. As regards the times of occurrence of the maxima for the different harmonics, there is no regularity except perhaps in the case of the second harmonic. In four (1, 6, 7, 8) the maximum of the second harmonic falls within two hours of the half time between the upper and lower meridian passage of the moon. In the others it falls within two hours of the times of upper and lower meridian passage.

Table II.—Relative Frequency of Earthquakes throughout the Lunar Day.

Hours.	Districts.										All Japan.
	1	2—5	6	7	8	9—10	11	12	13	14—15	
1	1·07	0·94	1·047	1·007	0·88	0·96	1·08	1·16	0·93	1·31	1·018
2	1·00	1·00	1·019	0·999	0·90	0·90	1·02	1·16	0·72	1·10	0·996
3	1·02	0·96	1·026	0·995	0·98	0·82	1·02	1·03	0·59	0·90	0·985
4	1·10	1·01	0·974	1·008	0·96	0·88	0·95	0·94	0·64	0·72	0·984
5	1·02	0·99	0·939	0·983	0·94	0·82	0·99	1·03	0·89	0·66	0·962
6	1·02	1·04	0·998	1·007	1·10	0·99	0·94	1·12	1·02	0·66	1·000
7	1·02	1·03	1·068	1·019	1·10	0·97	0·95	1·03	1·10	0·69	1·020
8	1·03	1·03	1·012	1·018	1·00	0·99	0·99	1·07	1·06	0·69	1·005
9	0·93	1·06	1·026	1·015	1·06	1·07	1·00	1·29	0·97	0·72	1·015
10	0·91	1·11	1·044	0·997	1·18	1·01	1·03	1·03	0·89	0·90	1·011
11	0·83	1·08	0·977	0·977	1·04	1·03	1·11	0·85	1·06	1·00	0·986
12	0·82	1·04	0·977	0·966	0·96	1·09	1·13	0·85	1·06	1·03	0·980
13	0·78	0·94	0·977	0·984	1·10	1·07	1·05	0·94	1·27	1·21	0·989
14	0·88	0·85	1·016	0·973	1·04	1·06	0·99	0·67	1·23	1·28	0·983
15	0·93	0·94	1·040	0·984	0·92	1·15	0·89	0·67	1·14	1·07	0·989
16	1·05	0·98	1·054	0·981	0·94	1·03	0·82	0·71	0·97	1·17	0·991
17	1·12	0·98	1·012	0·992	1·06	0·99	0·85	0·63	0·97	1·17	0·995
18	1·12	1·03	1·009	1·003	0·98	1·07	0·90	0·45	0·76	0·93	0·997
19	1·05	1·02	0·988	1·023	0·96	0·96	0·94	0·67	0·76	0·86	0·995
20	1·06	0·96	0·970	1·018	1·02	0·88	0·98	0·76	0·97	1·00	0·994
21	1·03	0·96	0·921	1·032	1·04	1·00	1·05	1·16	1·02	0·86	1·004
22	1·05	0·95	0·921	1·028	0·98	1·06	1·05	1·34	1·14	1·00	1·010
23	1·05	1·03	0·974	1·004	0·94	1·04	1·04	1·52	1·31	1·27	1·023
24	1·05	1·03	0·995	0·984	0·98	1·03	1·12	1·43	1·40	1·41	1·025
25	1·10	1·01	1·006	1·021	0·94	1·13	1·12	1·52	1·10	1·38	1·043

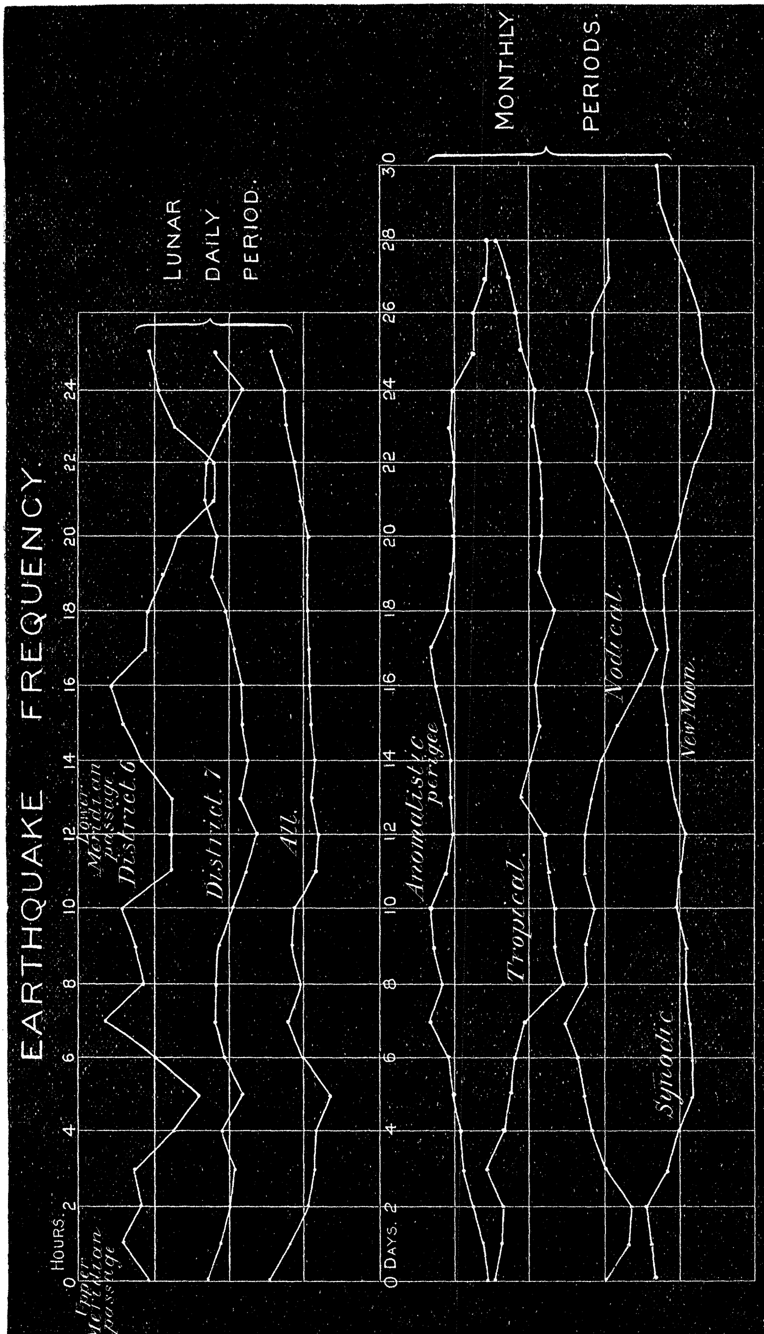

EARTHQUAKE FREQUENCY.
LUNAR DAILY PERIOD.
MONTHLY PERIODS.
HOURS.
DAYS.
Upper Meridian passage
Lower Meridian passage
District 6
District 7.
All.
Anomalistic perigee
Tropical.
Nodical.
New Moon.
Synodic

Table IV.—The Coefficients c and α, the amplitudes and phase-coefficients.

District.	c_1.	c_2.	c_3.	c_4.	α_1.	α_2.	α_3.	α_4.
1	94·4	68·7	46·9	16·6	7·85	9·95	2·08	3·43
2—5	29·9	36·5	32·4	35·2	24·2	4·33	0·88	2·95
6	18·4	20·7	29·9	14·6	21·8	11·5	1·79	5·65
7	13·0	16·4	3·17	8·98	6·7	7·9	1·3	6·1
8	54·2	45·8	10·0	6·17	20·2	9·03	2·53	2·07
9—10	65·0	56·9	53·8	5·26	15·9	3·94	3·0	1·92
11	42·8	91·5	32·5	26·0	3·55	4·19	6·91	1·53
12	245·0	233·0	111·5	36·7	3·38	4·93	3·57	4·48
13	73·9	167·0	193·0	7·48	15·1	4·62	3·9	1·09
14—15	175·0	247·6	91·9	41·5	11·2	2·78	2·79	1·75
All	10·3	17·9	10·9	3·97	6·62	7·97	2·42	2·43

A comparison of these times with the times of high water in the various districts failed to establish any relation. We are forced to the conclusion that if there be any lunar-diurnal periodicity imposed upon earthquake frequency, it is the result of tidal stresses acting directly on the approximately rigid crust of the earth, and not indirectly through the loading due to the ocean tides.

Because of the comparatively great number of earthquakes the results for districts 6 and 7 are the most important. During the eight years under discussion, the shocks in district 6 occurred with normal frequency. All were comparatively small; none were disastrous. On the other hand, the case of district 7 is altogether peculiar. In general, this is a comparatively quiet district; but the great disaster of October 28, 1891, was followed by a vast number of after-shocks. These show distinct daily and half-daily periodicities, the latter having the greater amplitude. Thus, from district 6, with its 1432 earthquakes distributed with fair uniformity over eight years of normal activity, and from district 7 with its 3632 earthquakes, almost wholly included in a short fierce interval of fourteen months, we obtain very similar evidence as to the existence of a lunar half-daily period in earthquake frequency.

The results for "All" depend, in the main, upon the statistics for districts 6 and 7. The curious way in which the comparatively prominent 1st harmonics of these two districts tend to cancel one another, is a warning of the danger of lumping together statistics of different countries or different seismic areas in the search for possible periodicities.

3. *The Lunar Monthly and Fortnightly Periodicities.*—There are five distinct kinds of months recognised by astronomers, namely :—

(1) The anomalistic month (27·545 days).
(2) The tropical month (27·322 days).
(3) The synodic month (29·531 days).
(4) The sidereal month (27·3228 days).
(5) The nodical month (27·212 days).

Of these, the last two cannot be regarded as having any influence on earthquake frequency, for the only conceivable effect is a tidal one, and the sidereal and nodical months have no necessary tidal relations. At the same time the periods of the sidereal and tropical months are so nearly the same that they can hardly be discriminated in the lapse of eight years. On the other hand, the anomalistic month may show itself in earthquake frequency, since the moon in perigee has a greater tidal action than when it is in apogee. Again, because of the moon's variation in declination, being now north of the Equator, now south, we may reasonably search for a tropical monthly periodicity. And, finally, the synodic or common month may make itself apparent, there being possibly a greater tidal stress when the moon is in syzygy (as in ordinary spring tides) than when the moon is in quadrature (as in neap tides).

The earthquakes were accordingly tabulated according to these four months, whose periods differ appreciably; the nodical month being also included. For, by analysing the statistics in terms of both the tropical and nodical months, we may be the better able to draw conclusions as to the real existence of one or other periodicity. The relative *daily* frequencies, as finally reduced, are given in Table VI, and the curves are shown in the figure.

As in the case of Table II, each of the tabulated numbers is the mean of five successive numbers, and is regarded as belonging to the time of the middle one of these five.

It should be mentioned—and the remark applies also to the former cases—that the number of earthquakes which really occurred during the last time interval was increased in the proper ratio; so that the frequency during this last interval was made comparable with the frequencies of the other intervals. It was interesting to find how admirably the number so obtained harmonised with its neighbours of the first and penultimate interval.

In all cases the obvious aftershocks of any earthquake occurring on the same day were neglected. The 3000 aftershocks of the great disaster of October 28, 1891, were also left out.

The earthquakes on which the discussion is based numbered from 4725 to 4741, the number varying slightly for each monthly period, since, at the beginning and end of the eight years' interval, there were always a few, differing for the different months, which did not make up a complete period, and were, consequently, neglected.

Each series of numbers was analysed harmonically as far as the

Table VI.—"Monthly" Frequencies.

Day.	Anomalistic, from apogee.	Tropical, from 0° decl. N. to S.	Nodical, from ascending node.	Synodic, from full moon.
1	0·919	1·077	0·937	1·064
2	0·945	1·072	0·925	1·081
3	0·976	1·107	0·998	1·029
4	0·980	1·069	1·032	1·000
5	0·999	1·052	1·056	0·961
6	1·013	1·040	1·068	0·963
7	1·061	1·006	1·103	0·964
8	1·033	0·902	1·045	0·984
9	1·058	0·928	1·051	0·980
10	1·064	0·930	1·025	1·002
11	1·023	0·945	1·050	0·999
12	1·002	0·952	1·047	0·983
13	1·005	1·020	1·037	1·009
14	1·012	1·000	1·011	1·029
15	1·021	0·978	0·964	1·030
16	1·048	0·982	0·901	1·042
17	1·061	0·974	0·858	1·032
18	1·022	0·936	0·896	1·039
19	1·010	0·969	0·901	1·039
20	1·004	0·967	0·939	1·005
21	1·006	0·964	0·981	0·985
22	1·000	0·975	1·018	0·965
23	1·017	0·991	1·011	0·918
24	1·004	0·987	1·044	0·905
25	0·952	1·020	1·028	0·939
26	0·955	1·035	1·028	0·945
27	0·920	1·054	0·992	0·973
28	0·906	1·086	0·994	1·020
29	—	—	—	1·045
30	—	—	—	1·060

first four harmonics, according to a formula identical with that already given, due regard being paid to the different periods and the time unit involved. The results are given in Table VII, the phase coefficients being given in days.

Table VII.—Amplitudes and Phases.

"Month."	c_1.	c_2.	c_3.	c_4.	α_1.	α_2.	α_3.	α_4.
Anomalistic ...	46·2	47·8	12·9	16·5	21·7	8·5	5·2	6·2
Tropical	54·7	40·7	23·1	17·2	6·0	1·9	7·9	2·4
Nodical	49·5	55·2	28·3	17·6	1·2	7·9	6·9	2·7
Synodic	11·0	52·1	24·5	4·7	13·7	2·7	7·7	0·6

A study of these tables discloses the presence of certain features which have no *raison d'être* on any rational theory of tidal stress.

The most important of these is the fact that the nodical month, which has no direct connexion with tidal stress periodicity, is characterised by harmonic amplitudes greater, on the average, than those corresponding to the other months. This is particularly evident in the graphs.

There are, however, other features which favour the hypothesis of seismic tidal stress, such as the occurrence in the vicinity of perigee of the Anomalistic 1st Harmonic amplitude; the lagging, by one day, behind full and new moon of the Synodic 2nd Harmonic maxima; the distinctly greater amplitude of the Synodic 2nd Harmonic as compared with those of the other harmonics—a fact which is in accord with the fortnightly succession of spring tides.

It is, certainly, a striking fact that the same statistics which, when grouped according to an approximately twenty-eight days' period, give a prominent 1st harmonic should, when grouped according to an approximately thirty days' period, give a comparatively small 1st harmonic but a prominent 2nd harmonic.

4. *General Conclusions.*—The conclusions are summarised under eight heads.

(*a*) There is evidence that the earthquake frequency in Japan is subject to a periodicity associated with the lunar day.

(*b*) The lunar half-daily period is particularly in evidence, both by reason of its relative prominence and the regularity with which, in each of two groups of the several seismic districts, its phase falls in relation to the time of meridian passage of the moon.

(*c*) There is no certain evidence that the loading and unloading due to the flow and ebb of ocean tides have any effect on seismic frequency.

(*d*) Hence we must look to the direct tidal stress of the moon, in its daily change, as the most probable cause of a range in frequency which does not exceed 6 per cent. of the average frequency.

(*e*) There is distinct evidence, both as regards amplitude and phase, of a fortnightly periodicity associated with the times of conjunction and opposition of the sun and moon.

(*f*) No definite conclusion can be drawn from the apparent monthly and fortnightly periodicities which seem to be associated with the periodic changes in the moon's distance and declination, for the simple reason that fully as prominent harmonic components exist when the statistics are analysed according to the periodic change in the moon's position relative to the *ecliptic*, and with this particular period no tidal stresses can be directly associated.

(*g*) Nevertheless, the value of the phase lends some support to the view that there is a real connexion between the change in the moon's distance and earthquake frequency, since the maximum frequency falls near the time of perigee.

(*h*) These conclusions have, in comparison with previous similar investigations, a peculiar value, inasmuch as they are based upon accurate statistics of fully 7000 earthquakes occurring within eight years in a limited part of the earth's crust, throughout which the seismic conditions may be assumed to be fairly similar from point to point.

February 11, 1897.

The LORD LISTER, F.R.C.S., D.C.L., President, in the Chair.

A List of the Presents received was laid on the table, and thanks ordered for them.

Communications from Professor OLIVER LODGE, F.R.S., and Dr. LARMOR, F.R.S., on the recent discovery by Dr. P. Zeeman of the effect of a magnetic field on the light emitted by a soda flame, were read by the Secretary.

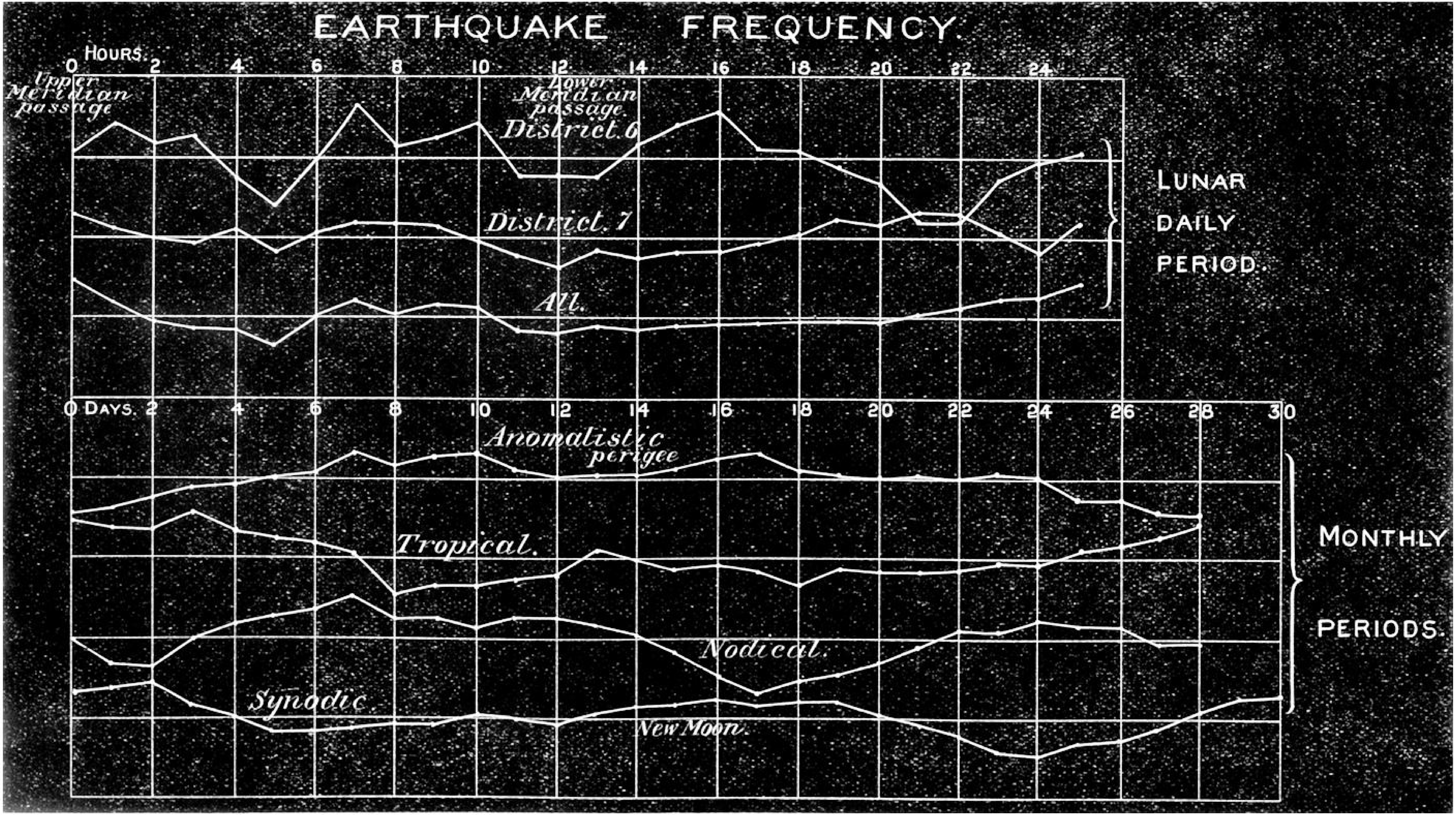
The following Papers were read :—

I. "The Oviposition of *Nautilus macromphalus*." By ARTHUR WILLEY, D.Sc., Balfour Student of the University of Cambridge. Communicated by ALFRED NEWTON, M.A., F.R.S., on behalf of the Managers of the Balfour Fund.

II. "Report to the Committee of the Royal Society appointed to investigate the Structure of a Coral Reef by boring." By W. J. SOLLAS, D.Sc., F.R.S., Professor of Geology in the University of Dublin.

III. "The artificial Insemination of Mammals and subsequent possible Fertilisation of their Ova." By WALTER HEAPE, M.A., Trinity College, Cambridge. Communicated by FRANCIS GALTON, F.R.S.

IV. "On the Regeneration of Nerves." By ROBERT KENNEDY, M.A., B.Sc., M.D. (Glasgow).


EARTHQUAKE FREQUENCY.
HOURS.
0 2 4 6 8 10 12 14 16 18 20 22 24
Upper Meridian passage
Lower Meridian passage
District. 6
District. 7
All.
LUNAR DAILY PERIOD.
0 DAYS. 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
Anomalistic
perigee
Tropical.
Nodical.
Synodic.
New Moon.
MONTHLY PERIODS.